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Radio and X-ray diffuse emission in six clusters of galaxies F. Govoni1,2 L. Feretti2 G. Giovannini2,3 H. Böhringer4 T. H. Reiprich4 M. Murgia2,3

F. Govoni (fgovoni@ira.bo.cnr.it)

Dipartimento di Astronomia, Univ. Bologna, Via Ranzani 1, I–40127 Bologna, Italy Istituto di Radioastronomia – CNR, via Gobetti 101, I–40129 Bologna, Italy Dipartimento di Fisica, Univ. Bologna, Via B. Pichat 6/2, I–40127 Bologna, Italy Max Planck Institut für Extraterrestrische Physik, PO Box 1603, D–85740 Garching, FRG

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Deep Very Large Array radio observations confirm the presence of halo and relic sources in six clusters of galaxies (A115, A520, A773, A1664, A2254, A2744) where a wide diffuse emission was previously found in the NRAO VLA Sky Survey. New images at 1.4 GHz of these six clusters of galaxies are presented and X-ray data obtained from the ROSAT archive are analyzed. The properties of clusters hosting radio halos and relics are analyzed and discussed. A correlation between the halo radio power and the cluster gravitational mass is presented. Galaxies: clusters : general – intergalactic medium – magnetic fields – Radio continuum: general – X-rays: general

Introduction

An important problem in cluster phenomenology regards cluster-wide radio halos, whose prototype is Coma C (Willson 1970).

Radio halos in clusters of galaxies are diffuse radio sources located in the cluster center with no obvious connection to the galaxy population of the clusters. They are characterized by a typical size of about 1 Mpc, regular shape, low surface brightness and steep radio spectrum. Other similar sources, but in general with irregular morphologies, are named relics. They are found at the cluster periphery. In a few clusters, both a central halo and a peripheral relic are present.

These radio sources demonstrate the existence of relativistic electrons and large scale magnetic fields in the cluster intergalactic medium (IGM).

The study of these sources is very important since they are large scale features, which are related to other cluster properties in the optical and X-ray domain, and are thus directly connected to the cluster history and evolution.

Radio halos and relics have always been considered very rare structures. However, thanks to the sensitivity of the radio telescopes and to the existence of deep radio surveys, the number of known halos and relics has recently increased.

Giovannini et al. (1999), using the NRAO Very Large Array (VLA) Sky Survey (NVSS, Condon et al. , 1998), searched for new radio halos and relics in the sample of X-ray-brightest Abell cluster (XBACs) presented by Ebeling et al. (1996).

The XBACs sample consists of clusters/subclusters from the catalogue of Abell et al. (1989) detected in the ROSAT All Sky survey (RASS) with X-ray flux $f_X > 5\ 10^{-12}$ erg cm^{-2} s^{-1} in the 0.1-2.4 keV energy range. This is an all-sky, X-ray flux limited sample, complete in the galactic latitude range $\mid b \mid \geq 20^\circ$ and in the redshift interval $z \leq 0.2$, but it contains also 12 clusters at lower galactic latitude and 24 clusters with redshift greater than 0.2 that meet the flux criterion. The NVSS was performed at 1.4 GHz with the VLA in D configuration. It has an angular resolution of 45″ (FWHM), a noise level of 0.45 mJy/beam (1σ) and covers all the sky north of Declination = –40°. Because of the lack of short baselines, Giovannini et al. (1999) used as a limiting redshift for the search of diffuse sources the value $z \geq 0.044$. Considering this redshift limit, and taking into account the declination limit of the NVSS, they searched for diffuse emission in 207 clusters. They found 29 clusters, 11 of which were already known in the literature to possess a radio halo or relic, whereas 18 were new detections.

To properly map these diffuse sources high sensitivity to the extended features is needed, but also a good resolution is necessary to distinguish a real diffuse source from the blend of unrelated sources.

We started a project to study all these new radio halo and relic candidates with improved sensitivity and resolution with respect to the NVSS. Here we present the data for the clusters A115, A520, A773, A1664,

A2254, A2744 which were included in the first run of observations. The remaining clusters are presently being analyzed and will be presented in a future work.

The similarity between the radio and the X-ray morphology, the high cluster X-ray temperature and luminosity, and the evidence of substructures in clusters with radio halos (e.g. Feretti 1999) indicate the importance to analyze the X-ray properties of the cluster containing these diffuse sources. To obtain X-ray information and to find correlations between the radio and the X-ray parameters in clusters with radio halos and/or relics we analyzed pointed ROSAT observations for these clusters.

Here we present new radio images of these clusters, and compare them with the X-ray emission.

In Sect. 2 we present the radio and the X-ray data. In Sect. 3 we give the radio and the X-ray images. In Sect. 4 we perform an X-ray analysis, while the discussion and conclusions are reported in Sect. 5.

We use a Hubble constant H_0=50 km s^{-1}Mpc^{-1} and q_0=0.5 throughout the paper.

table General properties of the clusters flushleft tabularccccc

Name z Richness BM type kpc/″

Data

Some general properties of the six clusters of galaxies analyzed here are given in Table 1. Deep radio images were obtained for all these clusters. The X-ray emission was analyzed using the data taken from the ROSAT public archive. The presence of sub-structures in X-ray images can give indications on the dynamical evolution of the clusters, however we also searched in literature for optical data indicating peculiar sub-structures in the galaxy distribution that could be interpreted in terms of cluster merging. As reported in the individual notes of the clusters, we found useful information for A115 and A520.

Radio observations

table VLA Observing Log flushleft tabularccccc

Name Frequency Bandw. Config. Date

table Primary flux density calibrators and phase calibrators flushleft tabularccc

Name Primary Cal. Phase Cal.

The radio data were obtained with the VLA at 1.4 GHz, in the C and D configurations for a total observing time of about 2 hours for each cluster in each configuration. The observing frequency and configurations were chosen in order to have a good sampling of short spacings, ensuring that a halo-type source could be easily detected and imaged.

The shortest baseline is 35 m, corresponding to $\simeq 175\lambda$. Therefore structures up to about $20'$ in angular size are fully imaged. We note that our sources are all smaller in size. Only for A1664 where D array observations are not available we have a lack of short baselines which can affect our image of the relic radio source as discussed in Sect. 3.4.

table*[t] X-Ray data from the ROSAT archive flushleft tabularcccccc

Name Detector texp. RA DEC ROR

table* Radio parameters flushleft tabularccccccccc

Name type S_{1400} LLS α P_{1400} P_{tot} Volume H_{eq}

The details of the radio observations are given in Table 2. The observations in D configuration were performed at distant frequencies within the same band, to obtain information on the spectral index of the diffuse sources.

The data were calibrated and reduced with the Astronomical Image Processing System (AIPS), following the standard procedure: Fourier-Transform, Clean and Restore. Self-calibration was applied to minimize the effects of amplitude and phase variations.

The source 0137+331 (3C48) or 1331+305 (3C286) was used as a primary flux density calibrator (see Table 3). The phase calibrator was observed every 20 minutes, approximately.

We first reduced separately the data from the two different configurations, for a consistency check. Final images were produced by adding together the C configuration data at 1365 and 1435 MHz, with the D configuration data at 1365 MHz. Images were produced with different resolutions, using the AIPS task IMAGR. The image with the highest available resolution ($\simeq 15''$) provides information on the discrete radio sources, while the low resolution map ($\simeq 50''$) allows the proper detection of the low brightness diffuse radio emission. All the data at 1665 MHz are affected by interferences. A determination of the spectral index images is therefore difficult and only a total spectrum can be estimated.

X-Ray data

figure* 18 cm!fig1.ps []Radio images at 1.4 GHz of the relic source in A115. Left panel: the FWHM is $15''\times$ 15 $''$; the noise level is 0.1 mJy/beam. Contour levels are: -0.4 0.4 0.7 1 2 4 6 10 19 32 57 97 169 292 400 mJy/beam. Right panel: the FWHM is $35''\times 35''$; the noise level is 0.1 mJy/beam. Contour levels are: -0.5 0.5 0.7 1 2 4 6 10 19 32 57 97 169 292 400 mJy/beam. The pattern around the strong source 3C28 it is due to dynamic range problems. The peak of the image is coincident with this radio galaxy and it is 0.96 Jy/beam. $A115_a$